A.3 Objective Function

In the objective function we minimize the following costs:

z = Capital and operating costs of new wind plants
+ Cost of new transmission for wind
+ Capital and operating costs of new CSP plants
+ Cost of new transmission for CSP
+ Capital cost of conventional generators
+ Fuel and operating costs of conventional generation
+ Capital cost of new transmission lines
+ Capital cost of new storage capacity
+ Fuel and operating costs of storage
+ Cost of a CO_2 tax

In equation form, with explanatory notes in brackets (below the lines to which they refer):[7] [8]

$$
\begin{aligned}
z \;=\; & \sum_{c,i,l} (\mathrm{WturN}_{c,i,l} + \mathrm{WturTN}_{c,i,l} + \mathrm{Wtur\_inregion}_{c,i,l}) \\
& \qquad \cdot \left(\begin{array}{c} CW_c \cdot cpop_{c,i,l} \cdot (1 + cslope_{c,i,l} \cdot Cost\_Inst\_Frac) \\ \cdot (1 - st\_Invincent_{i \in states}) \\ + CWOM_c + CF_{c,l} \cdot (1 - st\_Prodincent_{i \in states}) \end{array} \right) \\
& \qquad\qquad \text{[wind capital and O\&M costs]} \\
+ \; & \sum_{c,i,l} \left(\sum_j \left(\mathrm{WN}_{c,i,j,l} + \mathrm{WTN}_{c,i,j,l} \right) + \mathrm{Welec\_inregion}_{c,i,l} \right) \cdot GridConCost \\
& \qquad\qquad \text{[wind capital and O\&M costs]} \\
+ \; & \sum_{c,i,j,l} \mathrm{WN}_{c,i,j,l} \cdot CF_{c,l} \cdot (TOWCOST \cdot Distance_{i,j} + PostStamp_{i,j}) \\
& \qquad \cdot (1 - SurplusMar_{c,i}) \cdot 8760/CRF \\
& \qquad\qquad \text{[cost to connect wind to grid on pre-2006 lines]} \\
+ \; & \sum_{c,i,l} \mathrm{WTN}_{c,i,j,l} \cdot TNWCOST \cdot Distance_{i,j} \\
& \qquad\qquad \text{[cost to connect wind to grid on new lines]} \\
+ \; & \sum_{g} \mathrm{WCt}_g \cdot CG_g \\
& \qquad\qquad \text{[excessive growth penalty on wind turbines]} \\
+ \; & \sum_{ginst,i} \mathrm{WCtinst}_{ginst,i} \cdot CGinst_{ginst} \\
& \qquad\qquad \text{[excessive growth penalty on wind installation]}
\end{aligned}
$$

[7] some subscripts, e.g. *wscp* on WturN in the first line of the objective function are elided here and in constraints, below, when they are immediately summed over and therefore have no bearing on the equation.

[8] All parameters used in the objective function and constraints can be found in the glossary, below.

$$+ \quad \sum_{c,i,l} \left(\sum_{wscp} \text{WNSC}_{i,l,wscp} \cdot WR2GPTS_{c,i,l,wscp} \right) \cdot CF_{c,l} \cdot 8760/CRF$$

[cost of spur line to connect new wind capacity to pre-2006 grid]

$$+ \quad \sum_{c,j,l} \left(\sum_{escp} \text{Welec\_inregion}_{c,j,l,escp} \cdot MW\_inregion\_dis_{c,j,escp} \right) \cdot CF_{c,l} \cdot 8760/CRF$$

[cost of spur line to connect new wind capacity to inregion load]

$$+ \quad \sum_{cCSP,i} \left(\text{CSPturN}_{cCSP,i} + \text{CSPturTN}_{cCSP,i} + \text{CSPtur\_inregion}_{cCSP,i} \right) \cdot (CCSP_{cCSP} + CSPOM_{cCSP})$$

[CSP capital and O&M costs]

$$+ \quad \sum_{cCSP,i,j} \left(\text{CSPN}_{cCSP,i,j} + \text{CSPTN}_{cCSP,i,j} + \text{CSPelec\_inregion}_{cCSP,i,j} \right) \cdot CSPGridConCost$$

[inregion CSP capital and O&M costs]

$$+ \quad \sum_{cCSP,i,j,m} \text{CSPN}_{cCSP,i,j} \cdot H_m \cdot CF_{cCSP,m} \cdot (TOWCOST \cdot Distance_{i,j} + PostStamp_{i,j})$$
$$\cdot (1 - CSPSurplusMar_{cCSP,i})/CRF$$

[cost to connect CSP to grid on pre-2006 lines]

$$+ \quad \sum_{cCSP,i,j} \text{CspTN}_{cCSP,i,j} \cdot TNWCOST \cdot Distance_{i,j}$$

[cost to connect CSP to grid on new lines]

$$+ \quad \sum_{cCSP,i,j,m} \left(\sum_{cspscp} \text{CspNSC}_{cCSP,i,cspscp} \cdot CSP2GPTS_{cCSP,i,cspscp} \right) \cdot CF_{cCSP,m} \cdot H_m/CRF$$

[cost of spur line to connect new wind capacity to pre-2006 grid]

$$+ \quad \sum_{cCSP,i,j,m} \left(\sum_{escp} \text{CspELEC\_inregion}_{cCSP,j,escp} \cdot CSP\_inregion\_dis_{cCSP,j,escp} \right) \cdot \frac{CF_{cCSP,m} \cdot H_m}{CRF}$$

[cost of spur line to connect new CSP capacity to inregion load]

$$+ \quad \sum_{gCSP} \text{CSPCt}_{gCSP} \cdot CGcsp_{gCSP}$$

[excessive growth penalty on CSP hardware]

$$+ \quad \sum_{gCSPinst,i} \text{CSPCtinst}_{gCSPinst,i} \cdot CGcspinst_{gCSPinst}$$

[excessive growth penalty on CSP installation]

$$+ \quad \sum_{n,q} \text{CONV}_{n,q} \cdot (CCONV_q + CCONVF_q + Ctranadder_q + GridConCost)$$

[capital and O&M costs for conventional generators]

$$+ \quad \sum_{n,p} \text{CONVT}_{n,p,m} \cdot H_m/CRF \cdot \left(TOCOST \cdot Distance_{n,p} + PostStamp_{n,p} \right)$$

[variable costs for transmission]

$$+ \quad \sum_{q,g} \text{CGconv}_{q,g} \cdot CCt_{q,g}$$

[excessive growth penalty on conventional capacity]

$$+ \sum_{n,p} \text{TPCAN}_{n,p} \cdot \mathit{TNCOST} \cdot \mathit{Distance}_{n,p}$$

[capital cost of new transmission lines]

$$+ \sum_{\mathit{TPCA\_G}} \text{TPCA\_CG}_{\mathit{TPCA\_G}} \cdot \text{TPCA\_Ct}_{\mathit{TPCA\_G}}$$

[excessive growth penalty on new transmission]

$$+ \sum_{n,m,q} \text{CONVgen}_{n,m,q} \cdot H_m \cdot \mathit{CCONVV}_{n,q}$$

[operating and fuel costs for conventional generators]

$$+ \sum_{n,m,q} \text{CONVP}_{n,m,q} \cdot H_m \cdot \mathit{CCONVV}_{n,q} \cdot \mathit{PcostFrac}_q$$

[increased operating cost for peaking power]

$$+ \sum_{n,m,q} \text{SR}_{n,m,q} \cdot H_m \cdot \mathit{CSRV}_{n,q}$$

[operating and fuel costs for spinning reserve]

$$+ \sum_{n,q} \text{QS}_{n,q} \cdot \mathit{CQS}$$

[cost for quickstart capacity]

$$+ \sum_{\mathit{geoclass},n} \text{GeoBin}_{\mathit{geoclass},n} \cdot \mathit{GeoAdder}_{\mathit{geoclass},n} \cdot \mathit{CCONV}_{\mathit{geothermal}} / \mathit{CCC}_{\mathit{geothermal}}$$

$$+ \sum_{\mathit{egsclass},n} \text{GeoEGSBin}_{\mathit{egsclass},n} \cdot \mathit{GeoAdder}_{\mathit{egsclass},n} \cdot \mathit{CCONV}_{\mathit{geothermal}} / \mathit{CCC}_{\mathit{geothermal}}$$

[supply curve-based cost for geothermal capacity]

$$+ \sum_{\mathit{bioclass},n} \text{BioGeneration}_{\mathit{bioclass},n} \cdot \mathit{CHeatRate}_{\mathit{biopower}} \cdot \mathit{BioFeedstockLCOF}_{\mathit{bioclass},n}$$

$$+ \sum_{\mathit{bioclass},n} \text{CofireGen}_{\mathit{bioclass},n} \cdot \mathit{CHeatRate}_{\mathit{cofire}} \cdot (\mathit{BioFeedstockLCOF}_{\mathit{bioclass},n} - \mathit{Fprice}_{\mathit{coal},n})$$

[supply curve-based cost for biomass feedstock]

$$+ \sum_{st,n} \text{STOR}_{st,n} \cdot (\mathit{CSTOR}_{st} + \mathit{FSTOR}_{st} / \mathit{CRF})$$

[capital and O&M costs for storage]

$$+ \sum_{n,m,st} \text{STORin}_{n,m,st} \cdot H_m \cdot (\mathit{VSTOR}_{st} \cdot \mathit{STOR\_RTE}_{st} + \mathit{Fprice}_{\mathit{CAES},n} \cdot \mathit{CAESHeatRate})$$

[operating and fuel costs for storage]

$$+ \sum_{st,\mathit{storagebp}} \text{STORAGEBIN}_{st,\mathit{storagebp}} \cdot \mathit{CGStorage}_{st,\mathit{storagebp}}$$

[excessive growth penalty on new storage]

$$+ \sum_{n,m,q} (\text{CONVgen}_{n,m,q} + \text{CONVP}_q) \cdot H_m \cdot \mathit{CONVpol}_{q,\mathit{CO2}} \cdot \mathit{CHeatRate}_q \cdot \mathit{CarbTax}$$

[cost of carbon tax on conventional generation]

$$+ \sum_{n,m,st} \text{STORout}_{n,m,st} \cdot H_m \cdot \mathit{STORpol}_{st,\mathit{CO2}} \cdot \mathit{CHeatRate}_{st} \cdot \mathit{CarbTax}$$

[cost of carbon tax on storage generation]

$$+ \quad \sum_{n,q} \text{COALLOWSUL}_{n,q} \cdot \textit{lowsuladd\_LCF}_n \cdot \textit{CHeatRate}_q$$

[surcharge for using low sulfur coal]

$$+ \quad \text{RPS\_shortfall} \cdot \textit{RPSSCost}$$

$$+ \quad \sum_{states} \text{St\_RPSshortfall}_{states} \cdot \textit{St\_RPSSCost}$$

$$+ \quad \sum_{states} \text{St\_CSPRPSshortfall}_{states} \cdot \textit{St\_CSPRPSCost}_{states}$$

[costs of shortfalls in failing to meet RPS requirements]

A.4 Constraints

The minimization of cost in ReEDS is subject to a large number of different constraints, involving limits on resources, transmission constraints, national growth constraints, ancillary services, and pollution. Unless specifically noted otherwise (see, for example, the wind resource limit below), these constraints apply to new generating capacity built in the time period being optimized.

The constraint name is shown with the subscripts over which the constraint applies. For example, in the constraint immediately below, the subscript *'c, i, l'* immediately following the name of the constraint implies that this constraint is applied for every class of wind *c*, every region *i*, and every location *l*. Because there are 356 regions, five classes of wind, and 3 locations, this first type of constraint is repeated 5,340 times (356x5x3).

A.4.1 Constraints on Wind

Wind Resource Constraint: For every wind class *c* and wind supply region *i*, the sum of all wind capacity installed in this and preceding time periods must be less than the total wind resource in the region.

WIND_RES_UC$_{c,i,l}$

$$\text{WturN}_{c,i,l} + \text{WturTN}_{c,i,l} + \text{Wtur\_inregion}_{c,i,l} \quad \leq \quad \max(0, \textit{WRuc}_{c,i,l} - \textit{WturO}_{c,i,l} - \textit{WTturO}_{c,i,l})$$

Wind Supply Curve: New wind of class *c* in region *i* at interconnection cost step *wscp* must be less than the remaining wind resource in that cost step.[9] The second constraint balances the wind on pre-2006 lines across the different supply curve points and is used to determine the cost of transmission required to reach the grid.

WIND_supply_curves$_{c,i,l,wscp}$

$$\text{WturN}_{c,i,l,wscp} \quad \leq \quad \max(0, \textit{WR2G}_{c,i,l,wscp})$$

WIND_EXISTRANS_BALANCE$_{i,l}$

$$\sum_{wscp} \text{WNSC}_{i,l,wscp} \quad = \quad \sum_{j} \text{WN}_{i,j,l}$$

[9] A preliminary optimization is performed outside and prior to the main model to construct a supply curve for onshore wind, shallow offshore wind, and deep offshore wind for each wind class *c* and region *i*. This supply curve is comprised of four quantity/cost pairs ($\textit{WR2G}_{c,i,l,wscp}$ / $\textit{WR2GPTS}_{c,i,l,wscp}$). The "curve" provides the amount of class *c* wind $\textit{WR2G}_{c,i,l,wscp}$ that can be connected to the pre-2006 grid for a cost between $\textit{WR2GPTS}_{c,i,l,wscp-1}$ and $\textit{WR2GPTS}_{c,i,l,wscp}$. This "pre-LP" optimization is described in more detail in Appendix G. The quantity $\textit{WR2G}_{c,i,l,wscp}$ is reduced after each period's LP optimization by the amount of wind used in the time period from that cost step.